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Acoustic properties of materials: a comparison of numerical and experimental methods.

Massimo Viscardi[1], **Pasquale Napolitano**[1]

[1] Department of Industrial Engineering, Aerospace Division, University of Naples "Federico II", Via Claudio 21, 80125 Naples, Italy

Email: massimo.viscardi@unina.it

Abstract. Acoustic simulations provide today a valid tool to simulate complex environments and complex interaction between acoustic and structure. Multiple methods are nowadays available with different degrees of accuracy and different applications. Simulation methods cover a wide frequency range with FE methods dominating the low frequency range. SEA mostly covers high frequency range with BEM covering an intermediate frequency range. Ray- tracing can work on the entire frequency range and is used when a large domain must be simulated. These methods require acoustic properties of materials to be implemented such as acoustic impedance or absorption and STL. The aim of this paper is to show different methods to provide these properties and discuss about the equivalence/difference of the numerical and experimental approaches under specific assumptions.

1. Framework description

In recent years simulation software's and methodologies have been largely improved. As a consequence the models today are extremely complex, and the multi-physic approach is dominant in nowadays simulations. This trend has influenced also acoustic and vibration fields.

Up to few years ago there was a well-defined mark line between low and high frequency range simulation; the first one mostly dominated by FE methods and the second one based one SEA approach. Since it's introduction BEM has crossed the line linking low frequency and high frequency providing a framework for a not well-defined middle frequency range.

Today this scenario is mostly changed and the boundaries between low frequency range and high frequency range is not as sharp as in the past. This is due to multiple reasons but is mainly related to the computational power that has exponentially increased, overcoming FEM limitations. FEM models can now be pushed up to 500-600 Hz with a reduced computational cost. SEA has been pushed towards low frequency introducing FEM/SEA hybrid methods to achieve SEA calculation down to 315-200 Hz third octave band.

BEM has become more efficient with fast multipole approach making BEM calculation affordable for a vast range of applications.

A different scenario involves ray-tracing methods. Its use has been limited for long time in architectural or civil applications but nowadays it has applied with positive results in industrial engineering (for example for pass-by calculation in automotive, railway and aeronautic).

What all these methods have now in common is that they can be used for acoustic simulation in different scenario and boundary conditions including frequency range and coupling. The great difficult in using these methods comes when we need to describe acoustic properties of the materials that constitute the boundary conditions of the fluid domain.

When evaluation interior noise using SEA methods, we need to provide valid information for STL and absorption in different format in order to achieve a good reliability and correlation. The same is true when we perform ray-tracing calculation for concert hall simulation or pass-by noise, we need to provide acoustic properties for a wide range of materials. Same consideration is valid for BEM, when we evaluate the exterior acoustic field for a vehicle in automotive we need to provide acoustic properties for tires, body, glasses, and acoustic screen under the vehicle; acoustic properties of ground are also important in order to capture the reflections.

This necessity for acoustic properties is less evident in FEM since it is mostly used for structural simulation. As said before the improvement in computational power and in FE methods have pushed FEM towards higher frequencies so now FEM may be used for acoustic simulations as well. This application is now mostly limited to automotive or small aircraft vehicle where the enclosed volume is small and computational cost still affordable. When FEM is used for acoustic simulation inside the vehicle different levels of approximations can be used, the most accurate calculation is done using well know trimmed body model. This model includes all trims inside the model and may include acoustic treatments as well. If few years ago was impossible in FEM to account for acoustic package properties with new elements introduction is now possible to include acoustic properties from acoustic package.

As a summary of what explained before multiple methods are nowdays available for acoustic simulations (FEM, BEM, SEA, ray-tracing) and all these methods require as input, among the others, the acoustic properties of materials involved in the vibro-acoustic path simulation.

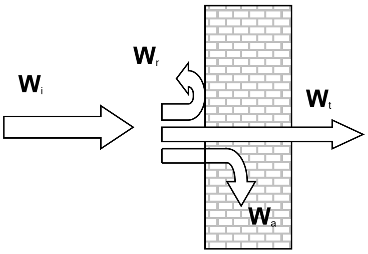
Despite the fast improvement in acoustic simulation capabilities material testing procedures for acoustic properties is still not a diffuse practice. Another element of confusion is the non-homogeneity in acoustic properties format required by different softwares. While some softwares require STL and absorption properties (ray-tracing) others require acoustic impedance for the material to be simulated (FEM, BEM). To make it even more complex SEA may accept absorption or DLF format.

In this scenario, among the different formats available is easy to get confused. The aim of this paper is to show and compare different methods both experimental and numerical to evaluate materials acoustic properties with purpose to feed numerical models.

2. Acoustic properties

In a more general contest, when we talk about acoustic properties, we mostly refer to sound transmission loss (STL or simply TL) and absorption (α).

To better understand what they are we can consider a simple scenario: a wave hitting a surface with a certain angle. When this happens the wave energy contribution is divided into three components (see figure 1). Part of the energy is reflected (Wr), part is absorbed by the wall (Wa) and part is transmitted through it (Wt). The amount of energy reflected, transmitted and absorbed according to the energy conservation principle must be equal to the amount of energy hitting the wall. The ratio between the absorbed energy and the hitting energy is a number in the range [0 – 1] with eventually 0 and 1 included, and this is the so-called absorption coefficient(α). In the same way the ratio between transmitted energy and hitting energy is called transmission coefficient (τ) and it is in the range [0 – 1] as well. The last contribution is the ratio between reflected energy and incident energy and is called reflection coefficient (r).



$$\alpha = \frac{W_a}{W_i}$$

$$\tau = \frac{W_\tau}{W_i}$$

$$r = \frac{W_r}{W_i}$$

Figure 1: Incident energy (Wi), reflected energy (Wr), absorbed energy (Wa) and transmitted energy (Wt).

The absorption coefficient (α) is worldwide known as the best representation of the capacity of a material to absorb noise and is a function of frequency. For what concerns the capacity to "do not transmit" noise, the STL parameter is generally used , whose definition is logarithmic representation of the inverse of the transmission coefficient:

$$STL = 10 * \log_{10}\left(\frac{1}{\tau}\right)$$

Both these parameters are commonly used in acoustic simulations.

The very open point is how we can obtain these parameters in an easy and reliable way. The road mostly people follow is to proceed with experimental measurements. In this case a small and well-known equipment is commonly used: the Kundt or impedance tube.

3. Kundt tube

The kundt tube as represented in Figure 2. Is a fast and easy to use equipment for absorption and STL measurements.

Figure 2: Typical example of Kundt tube.

The specific behaviour and math behind Kundt tube is far beyond the purposes of this paper but to help reader to better understand the following considerations, few concepts are given. When operating the tube two measures are required to cover a frequency range from 100 Hz to 8 kHz. This is due because a relationship exists between the diameter of the tube and the frequency range we can analyse. The larger is the tube the lower the frequency range covered. To standardise the procedure of measurement and provide standard-like measures two diameters are commonly used; a 10 [cm] diameter that covers frequencies up to 1600 Hz and a diameter of 2 [cm] for frequencies up to 8 kHz.

A different tube configuration is used for absorption and STL measure. In both cases a double diameter option (10 cm and 2 cm) is used but a closed end is used for absorption coefficient and a double tube configuration is used for STL.

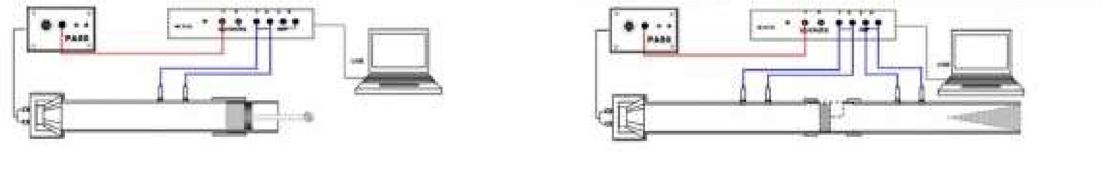


Figure 3: kundt tube respectively for absorption measurement (left side) and STL measurement (right side).

The tube provides a simple method for absorption and STL measurement, but it can't measure directly the properties. What the tube does is to measure the acoustic impedance of the material based on phase delay among the used microphones. The acoustic impedance is the fundamental parameter measured with the tube; absorption and STL are derived quantities.

Despite its simplicity the Kundt tube show some limitations that can totally downgrade results for some applications.

The most relevant is the limited size of the sample. A small sample such as the one required for Kundt tube test (10 cm and 2 cm diameter) does not account for modal behaviour of the sample. Neglecting the modal behaviour of the sample can lead to relevant errors in simulation when the modal behaviour is dominant. The simplest way to include modal and, in general, flexural behaviour of samples is to use larger samples. In order to do this, different measurements techniques, need to be introduced.

The second, but less limiting, consideration is about how absorption and STL are calculated starting from acoustic impedance. Of course, this is not a problem for a wide range of methods where the acoustic impedance is the input parameter (most likely FEM and BEM) but can be another source of error for methods where absorption and STL are the required parameters (most likely SEA and ray-tracing).

4. Alfa cabin

When the size of sample increase there is no common method for acoustic parameters measurement. Two different methods have been developed. For absorption coefficient the method used is the alfa cabin as shown in Figure 4.

Figure 4: Alfa cabin interior.

The alfa cabin is a sort of indirect measure of absorption as well. The cabin measures the reverberation time directly. The reverberation time measure is performed in two different cases. The first measure is performed when the cabin in empty. A second measure is performed when the material sample is laying on the cabin floor (as shown in Figure 4 above). The difference in reverberation time through the Sabine equation can be related to the material absorption.

The main difference between alfa cabin and Kundt tube, other the size of the sample used, is the type of acoustic field generated to measure the absorption; incident for Kundt tube, diffuse for alfa cabin.

The differences between the two methods can lead to statistically relevant differences in results obtained with the two methods.

The measures performed in alfa cabin may include different sources of errors, first is the edge effect on the samples. The measure based on reverberation time can lead sometimes to absorption coefficients greater than 1. Despite this is strictly forbidden by the definition itself of absorption coefficient this is due to the conditions of test and not really a physical behaviour.

5. Two chambers for STL

For STL measurements, specific equipment's must be used; among them, the double room set up is mostly used. This set-up, as shown in Figure 5, measure the acoustic energy left and right side of the element under test.

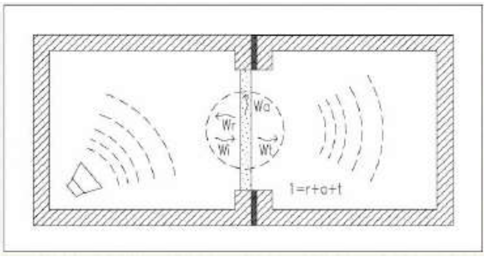


Figure 5: Two chambers set up for STL measurements.

In this set up an acoustic source is activated in the first room (left one) to create a diffuse acoustic field. The aim of this method is to calculate the acoustic energy both in left room (emitting room) and right one (receiving room).

Since the acoustic energy is not easy to measure a different parameter must be used. The parameter we can measure easily is the sound intensity (I) using a sound intensity probe. It is possible to measure the sound intensity in the receiving room using a probe and scanning the surface of the sample to obtain the intensity in the receiving room (Ir). For emitting room, a more simple method can be applied; considering the field diffuse inside the room we can find a relationship between sound intensity in the emitting room (Ie) and sound pressure level in the room (SPLe) with the following relationship

$$Ie = SPLe - 6$$

The STL is generally defined as the difference between the sound intensity in the emitting room and receiving room.

$$STL = Ie - It = SPLe - 6 - It$$

This method is reliable and can be used to calculate the STL for a wide range of samples in different conditions.

6. Numerical methods

The methods shown above are useful to measure absorption and STL when sample is available. Some of them are fast but inaccurate, other require more time and effort providing results reasonably more accurate. The results coming from test can be easily used in numerical models for acoustic simulation. But when testing is not an option different approaches must be used.

A full set of numerical models can be used to simulate the acoustic properties of materials both for acoustic impedance and for STL / absorption.

Multiple different models are available to calculate the acoustic properties. Most of them are semi-empiric and work on two different levels.

The first level is the one of the acoustic properties neglecting the flexural behaviour of the material; the second one includes elastic and mass properties.

The advantage of these models relies on the opportunity to simulate acoustic behaviour of even complex lay-up of different materials with a good accordance with experimental results.

The main drawback of these model is that specific properties to include into the model are needed. Simplest model is the Miki one where a parameter known as air flow resistivity (AFR) is required. It is a measure of how easily the air flow through the material under specific pressure condition and can be measured with a specific set-up.

More complex models require tortuosity (a measure of the tortuosity of the path the air walks inside the material), porosity (the ration between empty space and solid space into the material), thermal length and viscous length (a low scale parameter related to the gaps inside the material).

Some parameters can be easily measured like AFR, porosity and tortuosity some others are really complex to calculate like thermal length and viscous length.

The simplest method we can use, as mentioned above, is the Miki model also know as the mono-parametric model since it requires only a parameter (the AFR).
The model is used to calculate two parameters, the acoustic impedance (Z) and the complex wave number (k).

$$Z_c = \rho_0 c_0 \left[1 + 5.50\left(10^3 \frac{f}{\sigma}\right)^{-0.632} - j8.43\left(10^3 \frac{f}{\sigma}\right)^{-0.632}\right]$$

$$k = \frac{\omega}{c_0}\left[1 + 7.81\left(10^3 \frac{f}{\sigma}\right)^{-0.618} - j11.41\left(10^3 \frac{f}{\sigma}\right)^{-0.618}\right]$$

Combining the two equations we can obtain two more parameters, the bulk modulus (K) and the complex mass (ρc).

$$K = \frac{Z_c \omega}{k} \qquad \rho_c = \frac{k Z_c}{\omega}$$

Surface impedance (impedance scaled with thickness) for the material can be calculated combining K and Zc and including the material thickness.

$$Z = -j\frac{Z_c}{\tan(Kh)}$$

The model stops here. And the more complex models do the same.
The advantage of this method is that the results in terms of acoustic impedance can be easily calculated and is comparable with the one obtained from Kundt tube.
Acoustic impedance is a material property and doesn't depend from the method used (unless the numerical or experimental errors in the model).
To go next step and calculate the absorption and STL we need to introduce a second step into the simulation. We need specific models.
The absorption can be calculated using the following equation

$$\alpha = 1 - \left|\frac{Z - \rho_0 c_0}{Z + \rho_0 c_0}\right|^2$$

Where Z is the acoustic surface impedance of the material. While ρ_0 and c_0 are air density and speed of sound respectively. This simple relationship relates the acoustic impedance with absorption for the case of incident noise. This correlates very well with results from Kundt tube due to the very similar boundary conditions.
Similar relationship exists for STL as shown below

$$TL = 10\log_{10}\left(\frac{1}{4}\left|T_{11} + \frac{T_{12}}{c_0\rho_0} + c_0\rho_0 T_{21} + T_{22}\right|^2\right)$$

Where

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cos(k_c d) & j\sin(k_c d) Z_c \\ \frac{j\sin(k_c d)}{Z_c} & \cos(k_c d) \end{bmatrix}$$

These results for STL, again, correlate very well with Kundt tube results.
If we want to go further and correlate results with alfa cabin and two chamber STL we need to further improve the models shown above.

For absorption we need to introduce a new model to keep in account the field in alfa cabin is diffuse and not incident. This can be done using the London formula:

$$\alpha = \frac{8r}{x^2+r^2}\left[1+\frac{r^2-x^2}{x(x^2+r^2)}\operatorname{atan}\left(\frac{x}{1+r}\right)-\frac{r}{x^2+r^2}\log_{10}(1+2r+x^2+r^2)\right]$$

Where r is the real part of surface impedance divided by the air impedance, and x is the imaginary part of surface impedance divided by the air impedance.
For STL in two chambers method we need to include mass and flexural properties for the material.

7. Experimental vs Numerical comparison

In Figure 6, the comparison between absorption data measured in alfa cabin and data simulated using Miki model and London equation for diffuse field are reported.
In Figure 7 a comparison between absorption data measured in Kundt tube and simulated using Miki model are also illustrated.
In Figure 8 a comparison is shown a comparison between test data (Kundt tube) and simulation for STL., are finally presented.

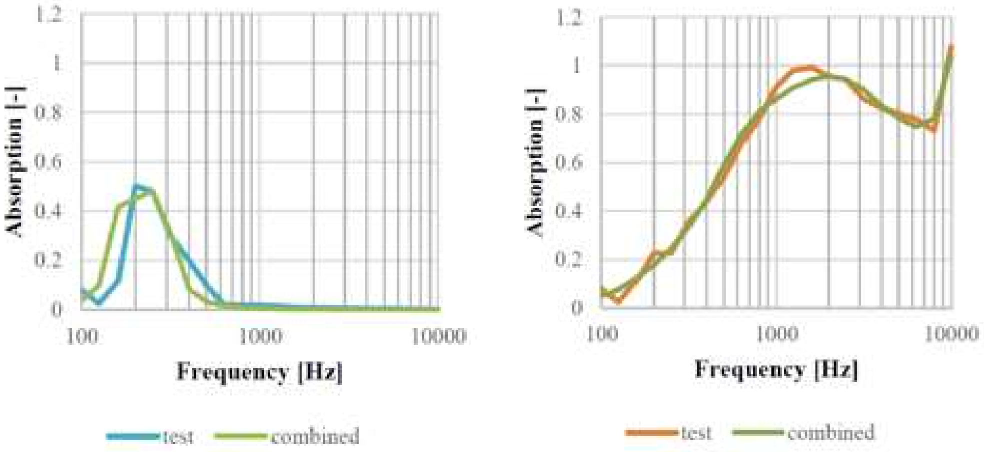


Figure 6: Absorption measured in alfa cabin (test) and simulated (combined) for two different scenarios.

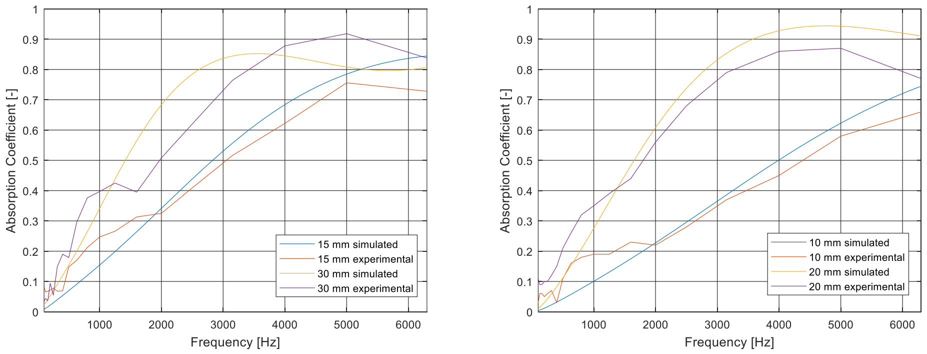


Figure 7: Absorption comparison simulated with Miki model and measured with Kundt tube.

8. Conclusions

Along the present paper, different methods to calculate acoustic properties for materials based on testing and simulation approaches have been introduced and compared.. Both approaches, if well assessed, can provide reliable results and can be used combined with more complex methods (FEM, BEM, SEA, ray-tracing) to improve acoustic simulations.

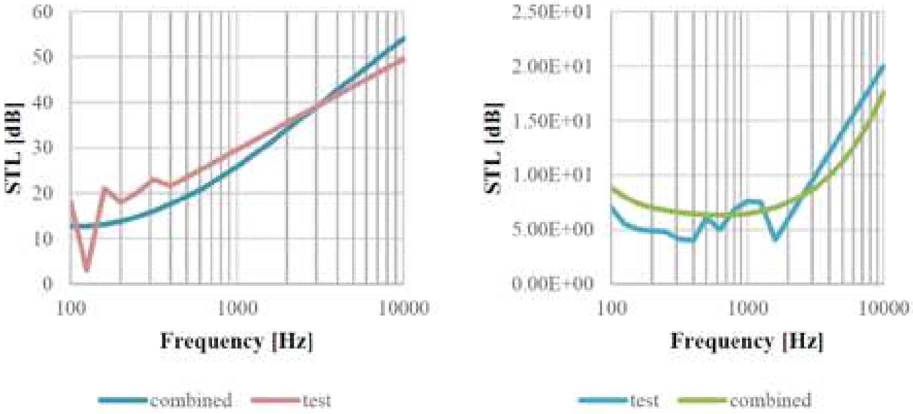


Figure 8: Kundt tube test (test) vs simulation (combined)

Test methods are reliable and can provide results for models but require a physical sample and time for testing. Numerical models can be faster and provide wide range of results in short time but require materials parameters (AFR, porosity, tortuosity, viscous length and thermal length).

None of these methods can work alone and a combination of two or more is always a best practice to follow.

As shown in paragraph 7 when a comparison between test and simulation is available a good grade of correlation can be achieved proving the validity of these methods. Choose where to start and which approach to follow depends on specific available data and timing. Under a theoretical point of view, the engineer can use different methods alone (or in combination) being sure each approach is equally valid providing comparable results if simulation and tests are performed under the same conditions.

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